Physics with Tau Leptons at CDF

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The $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions produced by the Tevatron result in many processes with tau leptons in the final state. The CDF Collaboration has studied these final states in Z and $t\bar{t}$ production, and has used tau leptons to search for evidence of Higgs, sparticle, and Z' production.

1. Introduction

Studies of tau leptons in $p\bar{p}$ collisions have a rich history, from backgrounds of potential new physical processes [1] to precision studies of lepton universality [2]. Since 2002, the Tevatron at Fermilab in Batavia, Illinois, has produced the highest energy ($\sqrt{s} = 1.96$ TeV) and luminosity ($\mathcal{L} > 1$ fb^{-1}) $p\bar{p}$ collisions to date. With these data sets, tau leptons can be used as probes for new processes with unprecedented sensitivities.

CDF has searched for a variety of hypothetical particles coupling to tau leptons. After establishing its tau reconstruction techniques with a measurement of the $p\bar{p} \to Z/\gamma^* \to \tau\tau$ cross section, CDF has applied these techniques to searches for Higgs and new gauge bosons, supersymmetric particles, and $t\bar{t}$ production.

2. Tau Reconstruction and Identification

The CDF detector consists of a range of components well-suited to tau identification. High-precision silicon and drift chamber tracking detectors measure a central ($|\eta| < 1$[3]) charged particle's production vertex to better than 100 μm, and its transverse momentum to $0.001/(\text{GeV}/c)$ p_T^2. Electromagnetic calorimetry measures central electron and photon energies with a resolution of $13.5\%/\sqrt{E_T} \oplus 1.5\%$, and their shower maximum positions to 1 mm.

The Tevatron's high frequency of $p\bar{p}$ detector crossings (2.5 MHz) prohibit collection of detector information at every crossing. Rather, event triggers are used to select particular physics pro-

cesses, including those with tau leptons in the final state. Exclusive tau triggers typically require at least two tau candidates, with at least one decaying hadronically. Hadronic tau (τ_h) candidates are defined by a 'seed' track with $p_T > 5$ GeV/c, and no other track with $p_T > 1.5$ GeV/c in a conical region 10-30° from the seed track. The trigger has better than 95% efficiency for τ_h candidates selected in the offline analysis.

In the full offline reconstruction, the tau lepton energy is measured by combining its track seed (typically corresponding to a charged pion) with the measured electromagnetic energy (typically corresponding to a neutral pion) in a narrow 0.3×0.5 $\eta - \phi$ cluster surrounding the seed.

Tau identification varies according to analysis, but generally includes selection distinguishing tau leptons from electrons or quark and gluon jets. Electron rejection is achieved through a requirement on the energy in the hadronic calorimeter, for example that $> 10\%$ of the tau momentum from charged tracks is reconstructed in the hadronic calorimeter. Quark and gluon jet rejection is usually accomplished through isolation energy requirements such as few tracks or π^0 candidates in a 30° cone surrounding the tau lepton candidate. Additional rejection can be achieved by requiring only one or three charged tracks in the tau cone, and by shrinking the tau cone size as its momentum increases. Finally, the mass of the reconstructed tau tracks and π^0 candidates can be required to be consistent with the tau mass.

Applying all tau requirements results in an efficiency of 60% for identifying τ_h in $Z \to \tau\tau$ events.

3. $p\bar{p} \to Z/\gamma^* \to \tau\tau$ Cross Section

The $p\bar{p} \to Z/\gamma^* \to \tau\tau$ cross section is measured using 350 pb^{-1} of data containing well-separated ($\Delta R > 0.9$) electron and τ_h candidates. At the Z resonance, central tau leptons have ≈ 45 GeV of transverse momentum. Since the electronic decay of the tau includes two neutrinos, the measured central electron has ≈ 15 GeV of transverse momentum. The on-line trigger selection requires a hadronic tau candidate and an electron candidate with $E_T > 8$ GeV. To ensure high efficiency of the trigger, offline selection requires electron $E_T > 10$ GeV and tau $p_T^\tau > 15$ GeV. The fraction of Z/γ^* events in the 66-116 GeV mass range with one electron and one hadronically-decaying tau passing the kinematic and geometric criteria is 1.1%.

The largest background contribution results from misreconstructing a quark or gluon jet as a hadronic tau decay. The dijet, $\gamma+$ jet, $W+$ jet, and $Z+$ jet processes all contribute to this background, which is roughly cut in half by requiring the net charge of the measured tau tracks to be opposite that of the electron track.

The dijet and $\gamma+$ jet backgrounds have topologies where the electron and τ_h candidates are opposite each other in the transverse plane ($\Delta\phi(e, \tau_h) \approx 180^o$). Since most of the energy in the event is along the $e - \tau_h$ line, any $\not{E}_T$ tends to lie along this line. The transverse mass ($m_T = \sqrt{2p_T^e \not{E}_T (1 - cos\Delta\phi)}$) is used to reduce background where the $\not{E}_T$ lies along the electron, and the magnitude of the vector sum of p_T^e and $\not{E}_T$ ($|\sum \vec{p}_T|$) is used to reduce background where the $\not{E}_T$ lies opposite the electron. A correlated requirement of $|\sum \vec{p}_T| > 24$ GeV or $m_T > 50 - 1.25|\sum \vec{p}_T|$ significantly rejects background while maintaining high efficiency (82%) for $Z \to \tau\tau$ events.

Further background rejection is achieved by requiring the electron track to not be consistent with a conversion ($\gamma+$ jet), m_T to be less than 50 GeV ($W+$ jet), and no additional electron calorimeter or track candidate consistent with a Z boson decay ($Z+$ jet). The combined acceptance for $Z/\gamma^* \to \tau\tau$ events of all the background rejection requirements is 76%. Table 1 shows the

Table 1
The background components to the $Z/\gamma^* \to \tau\tau$ sample, the number of observed data events, and the extracted number of $Z/\gamma^* \to \tau\tau$ events.

Process	Number of events
$Z/\gamma^* \to ee$	$35 \pm 1 \pm 7$
$W+$ jet	$37 \pm 4 \pm 5$
$\gamma+$ jet	$48 \pm 2 \pm 12$
Dijet	69 ± 4
Total background	$188 \pm 6 \pm 15$
Data	504
$Z/\gamma^* \to \tau\tau$	$316 \pm 23 \pm 15$

total background, the number of data events, and the extracted number of $Z/\gamma^* \to \tau\tau$ events. The signal to background ratio is better than 3/2 for this analysis.

The systematic uncertainties on the cross section measurement are dominated by the luminosity (5.8%) and background estimate (4.7%). Other uncertainties arise from determining the identification and trigger efficiencies, which respectively contribute 3% and 2% for tau leptons, and 1.9% and 2% for electrons. Finally, geometrical and kinematic acceptance uncertainties (including those due to parton distribution functions) are 3%, and uncertainties on the topology cuts are 2.8%. The limiting luminosity uncertainty is almost as large as all the other uncertainties combined (7.7%).

The cross section is measured to be:

$$\sigma(p\bar{p} \to Z/\gamma^*) \times Br(Z/\gamma^* \to \tau\tau) =$$
$$265 \pm 20 \text{ (stat)} \pm 21 \text{ (sys)} \pm 15 \text{ (lum) pb.} \quad (1)$$

The measurement is consistent with the theoretical prediction (250.3 pb) [4] and the corresponding measurement in the muon decay channel (261 pb), both of which have negligible uncertainties compared to the statistical uncertainty on the $p\bar{p} \to Z/\gamma^* \to \tau\tau$ cross section. Figure 1 shows the invariant mass constructed from the electron, τ_h, and $\not{E}_T$ combination. Since the z component of the energy imbalance is not included, the distribution peaks below the Z mass.
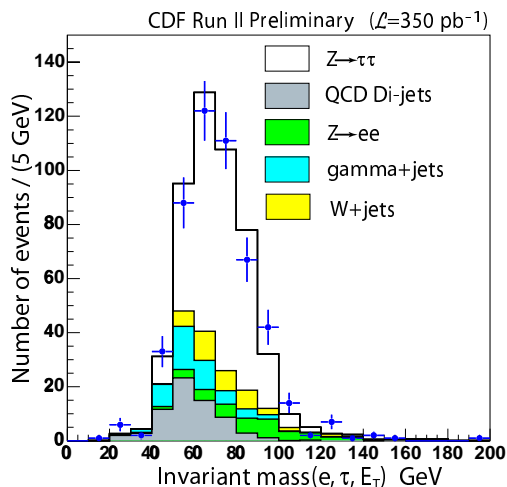
Figure 1. The invariant mass of $Z \rightarrow \tau\tau$ candidates, constructed from the electron, τ_h, and $\not{E}_T$ momentum vectors.

4. Search for $t\bar{t}$ Production

The decay of the top quark to a final state with tau leptons has never been observed. This final state is predicted to have the same rate as the electron or muon final states, since the top decays to Wb with a branching ratio of nearly 100%. CDF has searched for $t\bar{t}$ production in the decay channel $bl\nu\bar{b}\tau\nu$, where l corresponds to an electron or muon.

The data set used for the search corresponds to 350 pb^{-1} of integrated luminosity and is collected with a trigger requiring a single central electron or muon. The offline selection requires the electron or muon to have > 20 GeV of transverse momentum, the presence of one jet with $E_T > 25$ GeV and a second with $E_T > 15$ GeV, $\not{E}_T$ ¿ 20 GeV, and a τ_h candidate with $p_T^\tau > 15$ GeV.

As with the $Z \rightarrow \tau\tau$ cross section, the dominant background results from quark and gluon jets misreconstructed as a τ_h. To reduce this background, all available tau identification criteria are applied, and in some cases made more restrictive. In addition, the transverse energy in a $\Delta R < 0.4$ cone surrounding the τ_h is required to be less than 10% of the τ_h energy. The contribu-
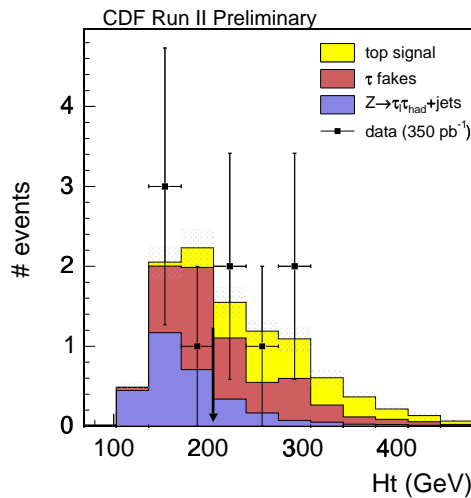

Figure 2. The total transverse energy H_T of the tau, lepton, jets, and $\not{E}_T$ in $l\tau jj\not{E}_T$ events. The requirement of $H_T > 205$ GeV significantly suppresses the $Z/\gamma^* \rightarrow \tau\tau + 2$ jets and the $W+(\text{jet} \rightarrow \tau_h)$ background components.

tion of this background to the selected sample is 1.8 events.

The other signficant background results from the $Z/\gamma^* \rightarrow \tau\tau + \geq 2$ jets process. Since the Q^2 of this process is lower than that of $t\bar{t}$ production, the total energy of the objects in the event can be used to suppress this background. This energy is defined as $H_T = \sum E_T^i$, where i includes the l, τ, jets, and the total energy imbalance of the event. A requirement of $H_T > 205$ GeV significantly suppresses background,as shown in Fig. 2. After all selection requirements, the background from $Z/\gamma^* \rightarrow \tau\tau + \geq 2$ jets is 0.7 events.

After all selection criteria are applied, 2.2 $t\bar{t}$ events are expected with a background of 2.8 ± 0.4. 5 events are observed in the data, corresponding to a $> 1\sigma$ excess over the expected background. The probability to observe 5 events given the background expectation alone is 15%. Extrapolating this result to the anticipated 4-6 fb^{-1} data set, the $t\bar{t} \rightarrow bl\nu\bar{b}\tau_h\nu$ process will be observable in Run 2.

5. Searches for Higgs Bosons

Because of its large mass relative to other leptons, the tau lepton is generally expected to have larger couplings to Higgs bosons, and final states with tau leptons should therefore be more sensitive to Higgs boson production. CDF has searched for neutral [5], singly-charged [6], and doubly-charged Higgs bosons in tau final states.

5.1. Neutral Higgs Boson Search

In the minimal supersymmetric model (MSSM), the neutral Higgs production cross section will be large if $\tan\beta$ is large (where $\tan\beta$ is the ratio of vacuum expectation values for the Higgs bosons coupling respectively to up- and down-flavor quarks and leptons). Since the Higgs branching ratio to tau pairs is also relatively large ($\approx 10\%$), the mass spectrum of ditau final states probes unexplored parameter space in the MSSM.

The data sets used in the search correspond to 310 pb^{-1} collected from the same electron $+ \tau_h$ trigger as the $Z/\gamma^* \to \tau\tau$ cross section measurement, and from a corresponding muon $+ \tau_h$ trigger with the same momentum thresholds. The backgrounds are similar to those of the $Z/\gamma^* \to \tau\tau$ data sample, but can be reduced by focusing on the higher invariant masses expected for the MSSM Higgs (prior searches set a lower bound of $\approx$93 GeV [5]). In particular, an $H_T > 50$ GeV threshold is applied, where H_T is defined as in the $t\bar{t}$ search without including the jets. Background from $W+$ jet, where the jet is reconstructed as a τ_h, is reduced by requiring the $\not{E}_T$ to be small or to lie along the direction of the bisecting axis between the τ_h and the lepton. Since the neutrinos from tau decays tend to be collinear with the tau at high tau momentum, the $\not{E}_T$ should lie along this bisecting axis.

After all selection, 496 ± 5 (stat) ± 28 (sys) ± 25 (lum) events are expected and 487 events are observed. Figure 3 shows the visible mass spectrum, where the visible mass is defined in the same way as the invariant mass for the $Z/\gamma^* \to \tau\tau$ cross section.

Despite a small excess in the data for $m_{vis} \approx$ 130 GeV/c^2, no evidence for a Higgs boson is

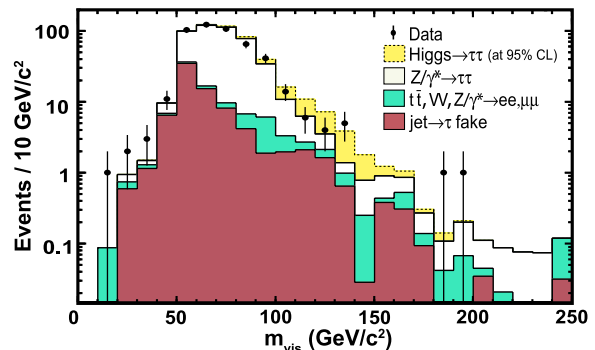Figure 3. The invariant mass of the lepton, τ_h and $\not{E}_T$ momentum vectors in the Higgs $\to \tau\tau$ search. For illustration purposes, the expectation for a Higgs with a mass of 140 GeV/c^2 is included.

observed. Corresponding 95% confidence level (C.L.) limits for a neutral Higgs in the mass-$\tan\beta$ plane are shown in Fig. 4, for two sets of MSSM parameters and two levels of mixing between the neutral Higgs bosons.

5.2. Charged Higgs Boson Search

In any extension to the SM that contains two Higgs doublets, such as the MSSM, the top can decay to H^+b if the charged Higgs boson is lighter than the top quark. CDF has performed a comprehensive analysis of our top cross sections measured with up to 193 pb^{-1}, and an earlier search for top decays to tau [7]. For non-zero branching ratio of $t \to H^+b$, CDF expects to observe a deficit in all decay channels except the tau channel, where an excess is expected, relative to the SM prediction.

The measured cross sections and the search for top decays to tau yield results consistent with the SM, so CDF sets limits on the H^+ mass as a function of $\tan\beta$ (Fig. 5). The search excludes new regions of MSSM parameters space and the expected factor of $20 - 30$ increase in data will extend our sensitivity significantly.

5.3. Doubly Charged Higgs Boson Search

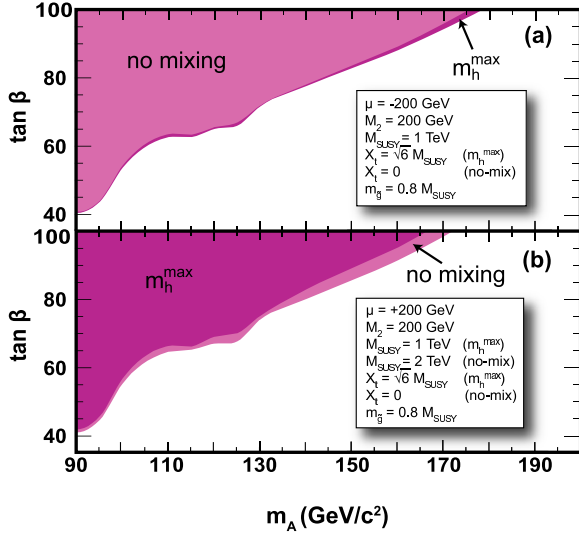Doubly-charged Higgs bosons ($H^{\pm\pm}$) [8] are predicted by models with a right-handed weak

Figure 4. The exclusion region (colored) for a neutral MSSM Higgs in the mass-tanβ plane. Two sets of MSSM parameters and two levels of mixing between the neutral Higgs bosons are shown.
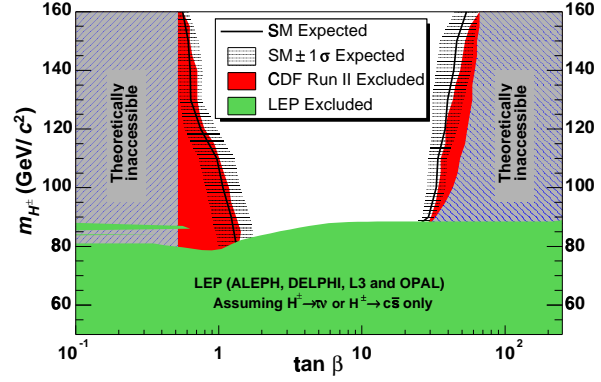

Figure 5. The exclusion region (colored) for a charged MSSM Higgs in the mass-tanβ plane. The CDF result is compared to the results from the detectors at the large electron-positron collider (LEP).

force (left-right symmetric models, or LRSM), which provides a mechanism for generating small neutrino masses. In a supersymmetric LRSM, $H^{\pm\pm}$ can be sufficiently light to be observable at the Tevatron. Doubly-charged Higgs bosons couple to leptons and other bosons, and for $H^{\pm\pm}$ masses less than twice the W mass, the lepton couplings dominate. These couplings are not predicted by the theory, unlike SM Higgs couplings, so it is necessary to search for all leptonic decays. CDF has published the result of a search for decays to electrons and muons [9], and have new results on a search for decays to $e\tau$ and $\mu\tau$.

At the Tevatron, $H^{\pm\pm}$ bosons are expected to be produced in pairs, leading to a striking 4-lepton signature, with resonances reconstructable with the same-sign lepton pairs. CDF separates its search into 3-lepton and 4-lepton categories. For the $\mu\tau$ search, CDF does not distinguish between μ and τ for the third lepton, and simply require an isolated track to increase efficiency. The 4-lepton category has very small background, 0.18

events in the combined $e\tau$ and $\mu\tau$ channels. The 3-lepton category requires some selection requirements to reduce the $Z+$ jet background, where the jet is misreconstructed as a tau. The additional selection are: same-sign and opposite-sign lepton masses consistent with a $H^{++}H^{--}$ topology; no opposite-sign electrons or muons near the Z mass; and significant H_T. The expected background and observed events after each progressive selection criterium are shown in Table 2.

No events are observed in 350 pb^{-1} of data, and limits on the $H^{\pm\pm}$ mass are set, assuming exclusive couplings to either $e\tau$ (114 GeV) or $\mu\tau$ (112 GeV). These are the world's highest limits for these channels over several orders of magnitude of coupling values.

6. Search for High-Mass Resonances

New particles with high mass, such as Z' bosons or sneutrinos, could preferentially couple to tau leptons and not be observable in other searches. CDF has searched for high-mass resonances decaying to tau pairs [10]. The search makes use of a trigger designed to select a hadronic tau and $\not{E}_T > 25$ GeV, allowing accep-

Table 2
The background components to the $Z/\gamma^* \to \tau\tau$ sample, the number of observed data events, and the extracted number of $Z/\gamma^* \to \tau\tau$ events.

Selection	Data	Background	Signal
$e\tau$ search			
Lepton ID	34	37.8 ± 1.3	2.9
m_{LS}, m_{OS}	29	35.4 ± 1.2	2.9
Z veto	8	9.7 ± 0.7	2.4
H_T	0	$0.24^{+0.27}_{-0.24}$	2.0
$\mu\tau$ search			
Lepton ID	28	30.0 ± 1.3	3.1
m_{LS}, m_{OS}	20	24.6 ± 1.2	3.0
Z veto	7	6.6 ± 0.7	2.4
H_T	0	0.27 ± 0.13	1.8

Figure 6. The invariant mass of the ditau system, using their visible energy and the $\not{E}_T$, in the high-mass resonance search.

tance for two hadronic tau decays.

The dominant background for this search is $Z \to \tau\tau$ production, which is small for very high masses. For high invariant mass of the visible tau energy ($m_{vis} > 120$ GeV), 2.8 ± 0.5 events are expected and 4 events observed in 195 pb^{-1} of data. Given the consistency of data with expectation, CDF sets a 95% C.L. limit on the cross section of high-mass scalar and vector particles. For a particle with a mass of 400 GeV, CDF excludes scalar (vector) particles if the cross section times branching ratio is greater than 1.4 (1.5) pb. Depending on the particular model, CDF can thus exclude Z' bosons or sneutrinos with masses below $350 - 400$ GeV.

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3. CDF uses a cylindrical coordinate system in which ϕ is the azimuthal angle, r is the radius from the nominal beamline, and $+z$ points in the direction of the proton beam and is zero at the center of the detector. T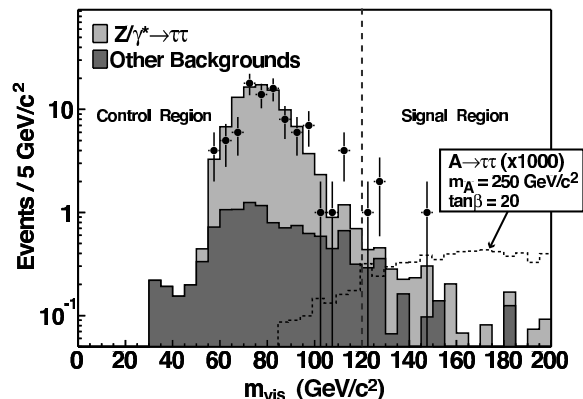he pseudorapidity $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the z axis. Separation in $\eta - \phi$ space is quantified by the variable $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. Calorimeter energy (track momentum) measured transverse to the beam is denoted as E_T (p_T), and the total calorimetric transverse energy imbalance is denoted as $\not{E}_T$. The combined track and calorimeter momentum calculation for hadronic tau decays is denoted as p_T^τ.
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